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Thermal characterization of oil palm fiber and eucalyptus in torrefaction

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ABSTRACT

Thermal behavior of biomass in torrefaction plays an important role in the operation of pretreatment. To understand the endothermic and/or exothermic characteristics of biomass in the course of torrefaction, an experimental system is conducted and two kinds of biomass (oil palm fiber and eucalyptus) are investigated. The results indicate that the thermal behavior is significantly influenced by the lignocellulosic composition in biomass and the torrefaction temperature. The thermal decomposition of hemicellulose is the dominant mechanism for oil palm fiber torrefied at 200 and 250 °C, whereas the thermal degradation of cellulose is crucial when the biomass is torrefied at 300 °C. Therefore, the heat of reaction of oil palm fiber increases with increasing torrefaction temperature. The torrefaction of eucalyptus is always endothermic, as a consequence of high cellulose contained in the biomass. It is less endothermic when the torrefaction temperature increases, presumably due to the char formation from cellulose thermal degradation and the exothermic lignin decomposition. As a whole, the values of the heat of reaction of the two samples are between −3.50 and 2.23 MJ/kg. The obtained results have provided a useful insight into the control of torrefaction operation and the design of torrefaction reactor.

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1. Introduction

Torrefaction is a promising thermal pretreatment process to upgrade solid biomass where the material is heated at temperatures of 200–300 °C in an inert atmosphere [1]. Torrefaction reduces the moisture in biomass and changes the hygroscopic biomass to the hydrophobic material, rendering the low affinity of water in torrefied biomass [2–5]. As a result, the upgraded materials can be stored for a long time and its utilization efficiency is relatively high. Torrefaction also reduces the costs of biomass transportation and storage [6] and makes the comminution of torrefied biomass easier [3,7–9]. Another important feature accompanied by torrefaction is that the energy density of torrefied biomass is higher than that of its parent biomass [4,10]. It has been reported that torrefaction has a positive effect on combustion [11,12], co-firing [13], co-gasification [4,14], and pelletization [15] of biomass. On account of these advantages, torrefied biomass is a potential alternative to coal consumed in industry.

Over the past several years, numerous studies have been performed on the effects of non-oxidizing torrefaction conditions upon the physical and chemical properties of biomass, such as weight loss, elemental variation, grindability, calorific value, energy yield, and thermal degradation kinetics of biomass [16–19]. Recently, the studies of oxidative torrefaction have also been carried out [20–23] to evaluate to the potential of using air as a carrier gas to upgrade biomass. From these studies, it is recognized that the quality and quantity of solid products are influenced by several operating conditions, such as temperature [17,19], duration [18], feedstock [20], particle geometry and size [16], and atmosphere or oxygen concentration [21–23].

When biomass is torrefied, the thermal behavior of the reaction is of the utmost importance in the pretreatment process. Specifically, the temperature control in the reactor will be disturbed by the endothermic and exothermic reactions in the course of torrefaction, thereby influencing the solid product quality. Up to now, many researchers have studied the heat of reaction of biomass pyrolysis using DTA (differential thermal analysis) or DSC (differential scanning calorimetry). He et al. [24] pointed out that the heat requirements (dry basis) for the pyrolyses of wheat straw, cotton stalk, pine, and peanut in the temperature range of 303–673 K were 523, 459, 646, and 385 kJ/kg, respectively. de Velden et al. [25]

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reported that the heat of reaction (dry basis) for spruce, poplar, eucalyptus, sawdust, sewage sludge, straw, corn, and sunflower in the temperature range of 313–823 K was between 207 and 424 kJ/kg. Fasina and Littlefield [26] discovered that energy required for removing the moisture of pecan shells was obviously higher than that for thermal decomposition, and the effect of heating rate on the energy requirement was slight.

Recently, a few studies concerning the heat of reaction of biomass torrefaction has been published. van der Stelt [27] performed beechwood torrefaction in a fixed bed reactor for 30 min to measure the heat of reaction. Corresponding to the torrefaction temperatures of 230, 250, and 280 °C, the values of heat of reaction for beechwood torrefaction were in the ranges of 425.3 to 1112.9, 21.5 to 1375.4, and −1516.4 to 1159.6 kJ/kg, respectively. They concluded that the thermal behavior during torrefaction became less endothermic or more exothermic with increasing torrefaction temperature. Bates and Ghoniem [28] developed a model using a two-step and first-order mechanism to describe willow torrefaction. They found that the exothermic behavior at the first stage of torrefaction was between 40 and 280 kJ/kg, while the thermal behavior of the second stage depended on temperature. Ohliger et al. [29] studied the torrefaction of beechwood chips at torrefaction temperatures of 270–300 °C and residence time of 15–60 min to evaluate the heat of reaction in a lab-scale reactor, and reported that the heat of reaction was between −199 and 148 kJ/kg.

Biomass is composed of cellulose, hemicellulose, lignin, and small amount of extractives. Therefore, the thermal behavior of biomass in torrefaction is highly related to the endothermic and exothermic reactions of the preceding constituents. The thermal characteristics of the constituents during pyrolysis have been outlined in some studies. For instance, the study of Yang et al. [30] indicated that the pyrolyses of hemicellulose and lignin were exothermic in nature, whereas the pyrolysis of cellulose pertained to endothermic reaction. Gomez et al. [31] pointed out that a higher content of lignin in biomass led to the higher exothermicity in a biomass decomposition process. Haykiri-Acma et al. [32] analyzed the thermal behavior of holocellulose and lignin extracted from hazelnut shells. They concluded that the exothermic extent of lignin in pyrolysis was larger than that of holocellulose, and the endothermic heat flow from cellulose was covered by hemicellulose resulting from the charring phenomenon. Mok and Antal Jr. [33] investigated the effects of pressure and carrier gas flow rate on the heat demand of cellulose pyrolysis, and showed that high pressure and low flow rate increased the exothermic char formation and reduced the heat of pyrolysis. Milosavljevic et al. [34] analyzed the thermochemistry of cellulose pyrolysis in an inert gas at heating rates from 0.1 to 60 K/min. They illustrated that the main cellulose thermal degradation pathway was endothermic; however, cellulose pyrolysis could be driven in the exothermic direction by the charring process which competed with tar formation, especially at low heating rates. Therefore, the char yield was the main factor to change the thermal behavior of cellulose pyrolysis. Cho et al. [35] studied the heat of reaction for cellulose pyrolysis at heating rates of 1–150 K/min, and observed that cellulose decomposition at high temperatures was endothermic. Nevertheless, the pyrolysis became exothermic at low temperatures because of the dominant mechanism of char formation.

In spite of many impressive studied conducted, the information of endothermic and exothermic characteristics in biomass torrefaction remains insufficient. The thermal behavior and net heat flow of biomass torrefaction are important factors in designing torrefaction reactors. Therefore, the objectives of this study are to conduct an experimental system and to investigate the thermal behavior of two types of biomass (i.e. oil palm fiber and eucalyptus) in the course of torrefaction. The thermogravimetric analyses of the biomass materials will be performed to aid in describing the thermal behavior. The results not only enable us to figure out the thermal degradation characteristics of biomass in different torrefaction environments, but also provide a useful insight into the design of torrefaction reactors.

2. Experimental

2.1. Material preparation and analysis

Oil palm is an important economic crop in some countries, especially in Malaysia, and oil palm fibers are abundant wastes from palm oil fruit harvest and oil extraction processing. On the other hand, eucalyptus is a fast growing plant which is the potential biomass for energy or fuel. Therefore, the two biomass materials were adopted and studied in this work. The eucalyptus was cut into blocks at the dimensions of 14 × 9 × 5 mm. The oil palm fiber was preliminarily ground by a shredder and sieved by vibrating screens. Afterward, its size was regulated between 40 and 100 mesh (i.e. 150–385 μm). To provide a basis for experiments, the raw biomass samples were dried in an oven at 105 °C for 24 h. The moisture content in biomass was measured by a moisture analyzer (Ohaus MB45). It suggested that almost all moisture was removed from the drying. Subsequently, the samples were placed in sealed plastic bags and stored in a desiccator at room temperature until experiments were carried out.

The analyses of the raw materials include proximate, elemental (ultimate), fiber, and calorific analyses. The proximate analysis was performed in accordance with the standard procedures of ASTM (American Society for Testing and Materials). The elemental analysis was carried out using an elemental analyzer (Elementar Vario EL III). Hemicellulose, cellulose, and lignin were analyzed following the fiber analysis adopted in a previous study [36]. The HHVs (higher heating values) of the samples were measured by means of a bomb calorimeter (IKA C2000 Basic). The results of the analyses are listed in Table 1.

The TGA (thermogravimetric analysis) was performed by use of a thermogravimetric analyzer (PerkinElmer Diamond TG/DTA). In the TGA, around 5 mg of sample at the sizes below 40 mesh (i.e.

Table 1
Proximate, elemental, fiber, and calorific analyses of biomass samples.

Biomass	Oil palm fiber	Eucalyptus
Photograph		
Proximate analysis (wt%, dry basis)		
Volatile matter (VM)	72.46	81.07
Fixed carbon (FC)	20.51	18.93
Ash	7.03	0.00
Elemental analysis (wt%)		
C	51.94	50.77
H	4.75	5.13
N	2.43	0.00
O (by diff.)	40.88	44.10
Fiber analysis (wt%)		
Hemicellulose	34.00	15.35
Cellulose	26.78	48.36
Lignin	16.08	21.26
Other	23.14	15.03
Higher heating value (MJ/kg)	17.13	18.38

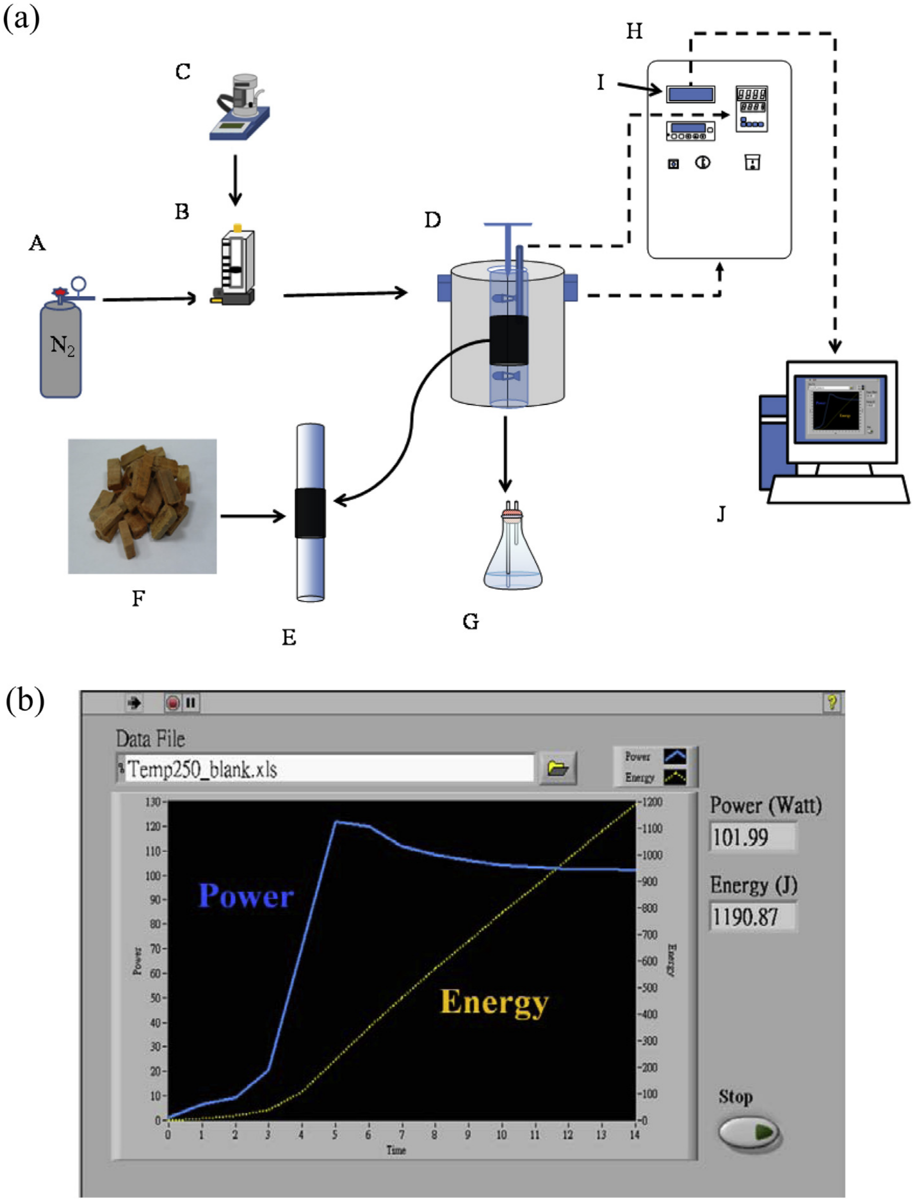
0.42 mm) was tested. The heating temperature in the analyzer ranged from 25 to 800 °C. Nitrogen at a flow rate of 100 mL/min (25 °C and 1 atm) was used as a carrier gas. In the test, the temperature of the analyzer was first raised from 25 °C to the torrefaction temperature at a heating rate of 20 °C/min. Then the sample was torrefied for 1 h followed by pyrolysis at a heating rate of 20 °C/min until the temperature reaching 800 °C.

2.2. Reaction system

The schematic of the experimental system is shown in Fig. 1a. The system, as a whole, was made up of a feeding unit, a reactor, a recording unit, and a product gas treatment unit. The feeding unit comprised a N_2 steel cylinder and a rotameter. Nitrogen was used as the carried gas. The rotameter, calibrated by a flow calibrator (Gillan-Stander Flow Cell-P/N 800266-1), was employed to control the volumetric flow rate of nitrogen. The reactor consisted of a glass reaction tube (32 mm i.d.), a vertical tube furnace, and a power controller. The length and inner diameter of the reaction tube were 680 mm and 32 mm, respectively. The tube was placed in the furnace which was controlled by the power controller to maintain the torrefaction temperature. In the furnace, the reaction tube was heated by directly contacting with heating elements. In the recording unit, a K-type thermocouple was placed at the center of biomass packed bed to detect the particle temperature so as to provide a reference for the power controller. A watt-hour meter was also installed to measure the supplied power. The temperature and power for torrefaction were monitored and recorded by a computer where the recording interface is shown in Fig. 1b. With regard to the product gas treatment unit, a conical flask was employed to remove tar and clean the exhaust gas.

2.3. Experimental procedure

In each experiment, the weight of sample was controlled at 10 g (±5%). The tested material was packed at the center of the reaction



Data File
Temp250_blank.xls
Power (Watt)
101.99
Energy (J)
1190.87

Fig. 1. The schematics of (a) reaction system and (b) power monitoring interface (A: N_2; B: rotameter; C: flow calibrator; D: vertical tube furnace; E: reaction tube; F: biomass; G: conical flash; H: power controller; I: watt-hour meter; J: recorder).

tube. The diameter of the packed bed was 32 mm and the packet bed length of oil palm fiber was controlled at 80 mm. Accordingly, the packing densities of oil palm fiber and eucalyptus were 0.156 g cm^{-3}. The sample was purged by N_2 at a flow rate of 100 mL/min (25 °C and 1 atm) for 15 min to ensure that the torrefaction process was in an oxygen-free environment. Thereafter, the sample was heated to the desired temperature, namely, the torrefaction temperature, followed by torrefaction for 1 h. The carrier gas (N_2) at the flow rate of 100 mL/min was continuously blown into the reaction tube to keep the system in an inert atmosphere and to remove volatiles produced in the reactor. The exhausted gas was cooled and washed in the conical flasks. After finishing torrefaction the solid residues were cooled to room temperature in the tube. The blank experiments without biomass inside the tube were also performed for evaluating the endothermic and exothermic reactions during torrefaction. Three different torrefaction temperatures of 200, 250, and 300 °C, corresponding to the light, mild, and severe torrefaction, were regarded. It was reported that 1-h torrefaction was appropriate to thermally upgrade biomass for solid fuels [37]; the duration was thus selected in this study.

To ascertain the experimental quality, the experiments of blank torrefaction at 250 and 300 °C were repeated three times and the distributions of energy consumption for the blank torrefaction are displayed in Fig. 2a and b, respectively. It can be seen that the difference in the curves among the three experiments is almost imperceptible. Table 2 demonstrates the relative errors between blank experiments and average results at the experimental time of 70 min and torrefaction temperatures of 250 and 300 °C. The maximum relative errors at 250 and 300 °C are 0.068 and 0.092%, respectively. This reveals that the reproducibility of the experiment was good. Furthermore, as shown in Table 2, the average energy of blank torrefaction at 300 °C and 70 min is 549.83 kJ and the maximum relative error is 0.092%. This means the energy uncertainty is ±0.505 kJ and the supplied energy of blank torrefaction is expressed as 549.83 ± 0.505 kJ.

3. Results and discussion

3.1. Thermogravimetric analysis of biomass

The thermogravimetric analysis (TGA) and DTG (derivative thermogravimetric) analysis of biomass are able to provide a fundamental insight into its thermal decomposition behavior. The distributions of TGA and DTG curves of the two samples at three torrefaction temperatures are displayed in Figs. 3 and 4, respectively. The distributions of temperature are also shown in the figures. When the torrefaction temperature is 200 °C (i.e. light torrefaction), only 3.17 wt% of oil palm fiber is decomposed in the course of torrefaction (Fig. 3a and Table 3). Because of this, as shown in Fig. 3b, the first peak (torrefaction peak) appeared in the DTG curve is not high. Following the light torrefaction, a double-peak distribution in the DTG curve of oil palm fiber is observed (Fig. 3b). The two peaks occurring at 307 and 359 °C correspond to the thermal decomposition of hemicellulose and cellulose, respectively [38]. With the torrefaction temperature of 250 °C (i.e. mild torrefaction), the weight loss of the biomass is 19.39 wt% and the peak at 307 °C in the DTG curve disappears. The torrefaction peak in the mild torrefaction is higher than that in the light torrefaction; this is due to the more pronounced consumption in hemicellulose and cellulose. In regard to the torrefaction temperature of 300 °C (i.e. severe torrefaction), there is a drastic drop in weight loss in the beginning of torrefaction and the weight loss is 25.92 wt%. A small peak at the temperature range of 360–600 °C is observed, stemming from the pyrolysis of lignin.

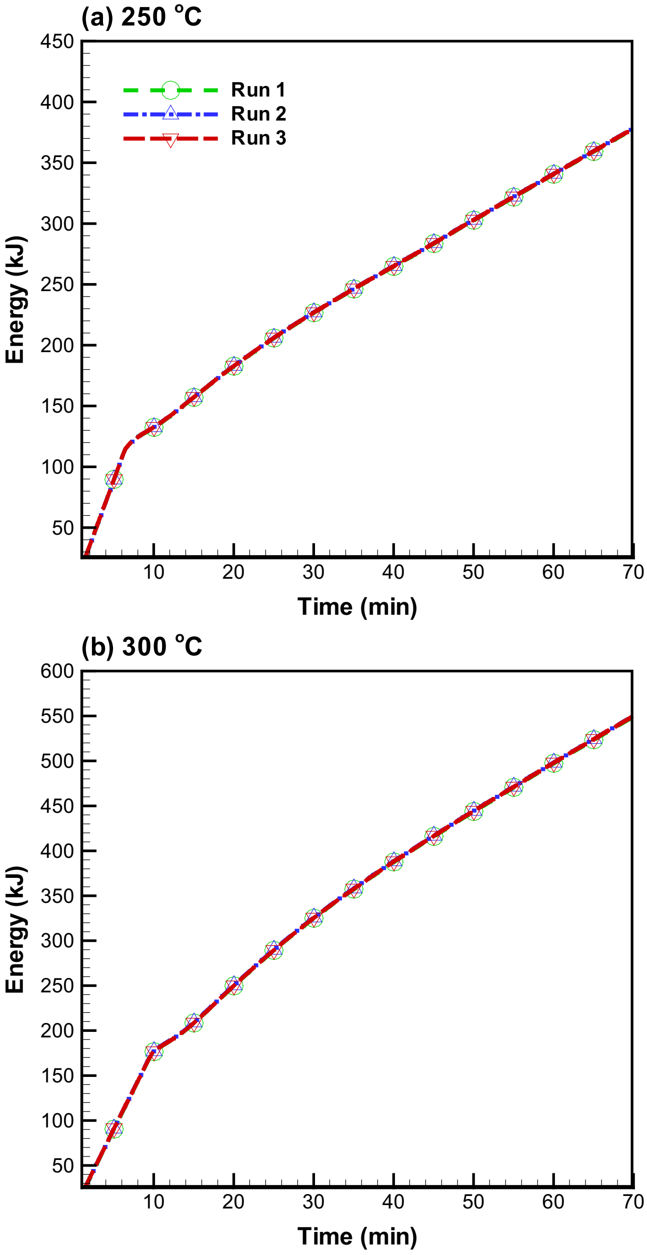


Fig. 2. Distributions of supplied energy for the blank torrefaction at (a) 250 and (b) 300 °C.

Corresponding to the torrefaction temperatures of 200, 250, and 300 °C, the weight losses of eucalyptus are 1.88, 12.3, and 33.35 wt %, respectively (Fig. 4a). This reveals that the severe torrefaction has a pronounced impact upon the thermal decomposition of

Table 2
A list of relative error of blank torrefaction at the experimental time of 70 min.

Torrefaction temperature (°C)	Run	Energy (kJ)	Average energy (kJ)	Relative error (%)
250	1	377.91		0.068
	2	378.38	378.17	0.056
	3	378.21		0.011
300	1	549.33		0.092
	2	550.23	549.83	0.072
	3	549.94		0.020

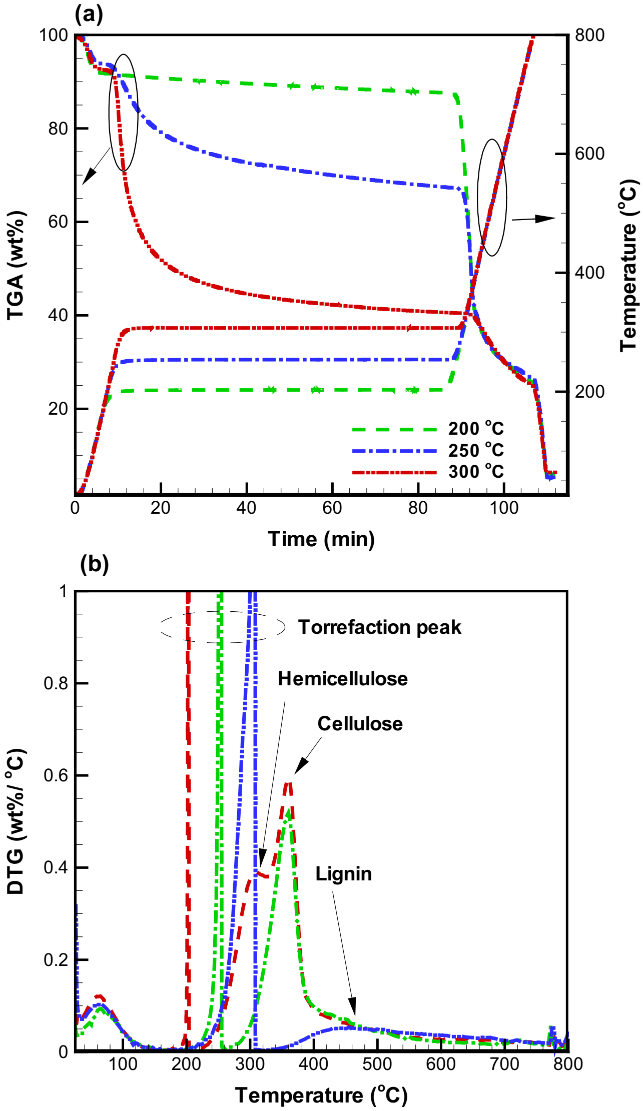


Fig. 3. Distributions of (a) TGA and (b) DTG of oil palm fiber.

eucalyptus. The peaks of hemicellulose and cellulose in the DTG curve of eucalyptus are located at 305 and 374 °C, respectively (Fig. 4b), which are close to those of oil palm fiber (Fig. 3b). The difference in the thermal degradation of the two species reveals that the impact of torrefaction on biomass depends intrinsically on the lignocellulosic nature in the material. It is noteworthy that the peaks of cellulose pyrolysis disappear after oil palm fiber and eucalyptus undergo torrefaction at 300 °C. This clearly reveals that the torrefaction duration of 1 h in the severe torrefaction has a significant impact on the thermal decomposition of cellulose, even though the torrefaction temperature is lower than 359 or 374 °C. In other words, the thermal degradation of cellulose in biomass is affected not only by temperature but also by duration.

3.2. Thermal behavior of oil palm fiber during torrefaction

Temporal temperature distributions in the reactor in the presence and absence of oil palm fiber at the torrefaction temperature of 200 °C are shown in Fig. 5a where the former and latter are referred to as biomass torrefaction and blank torrefaction, respectively, for simplicity in illustration. Before the temperature reaches 200 °C, its rising in blank torrefaction is faster than that in biomass torrefaction, resulting from no biomass absorbing heat. It takes approximately 16–17 min for the temperature reaching 200 °C in both the blank and biomass torrefaction. In examining supplied power, Fig. 5b indicates that more power is given in biomass torrefaction than in blank counterpart before the heating time of 12 min. Thereafter, the power supplied in biomass torrefaction is lower than that in blank torrefaction. In a previous study [1], it was discovered that light torrefaction mainly affected hemicellulose rather than cellulose and lignin. Yang et al. [30] pointed out that the pyrolysis of hemicellulose and lignin was exothermic, whereas the thermal degradation of cellulose was endothermic. The hemicellulose content in oil palm fiber is higher than the cellulose one (Table 1), and the former contributes heat in the light torrefaction. This is the reason why the supplied power in biomass torrefaction is lower than in blank torrefaction after the heating time of 12 min. On account of the exothermic reaction from hemicellulose decomposition, the temperature in biomass torrefaction at the heating time of 16–31 min is even higher than that in blank torrefaction (Fig. 5a). Upon inspection of the profiles of energy consumption of blank and biomass torrefaction and their difference,

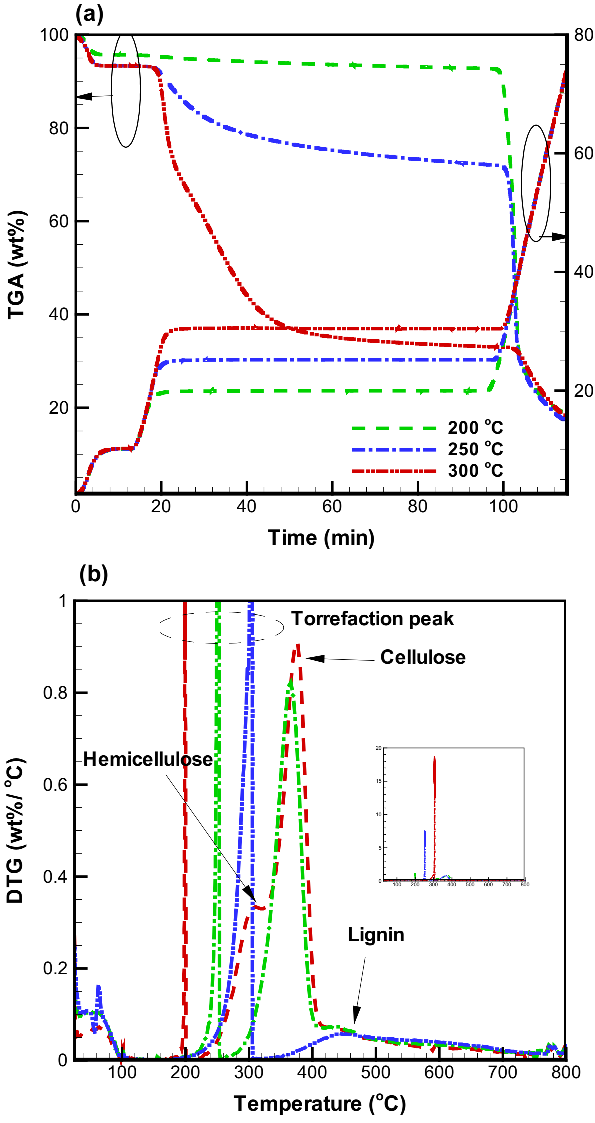


Fig. 4. Distributions of (a) TGA and (b) DTG of eucalyptus.

Table 3
A list of biomass weight loss (wt%) during torrefaction in thermogravimetric analysis.

Biomass	Torrefaction temperature (°C)		
	200	250	300
Oil palm fiber	3.17	19.39	25.92
Eucalyptus	1.88	12.30	33.35

Fig. 5c depicts that additional energy is required for the torrefaction of oil palm fiber before the time of 21 min. The maximum required energy is 12.4 kJ, which develops at 12 min. The required energy is used for pre-drying, post-drying, and the intermediate heating of biomass. The three processes correspond to the release of free water, physically bound water, and light volatiles, respectively [8,39]. The processes are also related to the evaporation of extra-cellulosic water from the cellulose components of biomass [40]. As a whole, the supplied energy during the light torrefaction is between −35.0 and 12.4 kJ and the net energy for the light torrefaction is −35.0 kJ (at 70 min).

In examining the torrefaction of eucalyptus at 200 °C, Fig. 6a depicts that the temperature of biomass torrefaction at the time between 10 and 30 min is lower than that of blank torrefaction. This reveals that heat liberated from hemicellulose degradation is not pronounced. As a result, the supplied power for biomass torrefaction is always higher than that for blank torrefaction after the time is longer than 10 min, as observed in Fig. 6b. Upon inspection of the profiles of energy consumption of blank and biomass torrefaction and their difference, Fig. 6c indicates that the minimum energy is −1.47 kJ which occurs at 12.5 min, resulting from the hemicellulose decomposition. When the time is longer than 14 min, the light torrefaction is characterized by an endothermic process. Overall, the supplied energy during the light torrefaction of eucalyptus is between −1.47 and 29.88 kJ and the net energy for the light torrefaction is 29.88 kJ (at 70 min). The thermal behavior of eucalyptus under light torrefaction is fairly different from that of oil palm fiber.

3.3. Thermal behavior in mild torrefaction

Time-dependent distributions of supplied energy for the mild torrefaction (i.e. 250 °C) of the two biomass species are presented in Fig. 7. The entire distribution of the mild torrefaction of oil palm fiber (Fig. 7a) is similar to that of light torrefaction (Fig. 5c). The maximum value in the curve is 15.1 kJ at 11 min. In addition to hemicellulose, small amount of cellulose is also decomposed, as shown in the DTG curve at 250 °C (Fig. 3b). The decomposition of cellulose is endothermic which absorbed some heat liberated from hemicellulose pyrolysis. As a consequence, the net energy for the mild torrefaction is −17.0 kJ, which is less exothermic compared to the light torrefaction. In regard to eucalyptus, Fig. 7b depicts that the torrefaction processes are characterized by stronger endothermic reactions and the maximum values in the curves is 24.9 kJ (at 22 min). This can be explained by more cellulose contained in eucalyptus (Table 1) and its consumption in the mild torrefaction. The strong endothermic reaction due to cellulose decomposition is also found in the study of Yang et al. [30].

3.4. Thermal behavior in severe torrefaction

Temporal distributions of supplied energy for the severe torrefaction (at 300 °C) of the two samples are plotted in Fig. 8. After the preheating process (<13 min), an exothermic process followed by an endothermic one is exhibited in the torrefaction of oil palm fiber (Fig. 8a). The exothermic reaction is contributed by the decomposition of hemicellulose and lignin, while the endothermic reaction (>50 min) is due to the pyrolysis of cellulose, as observed in DTG curve (Fig. 3b). The torrefaction of eucalyptus (Fig. 8b) is endothermic throughout the entire pretreatment process, but the

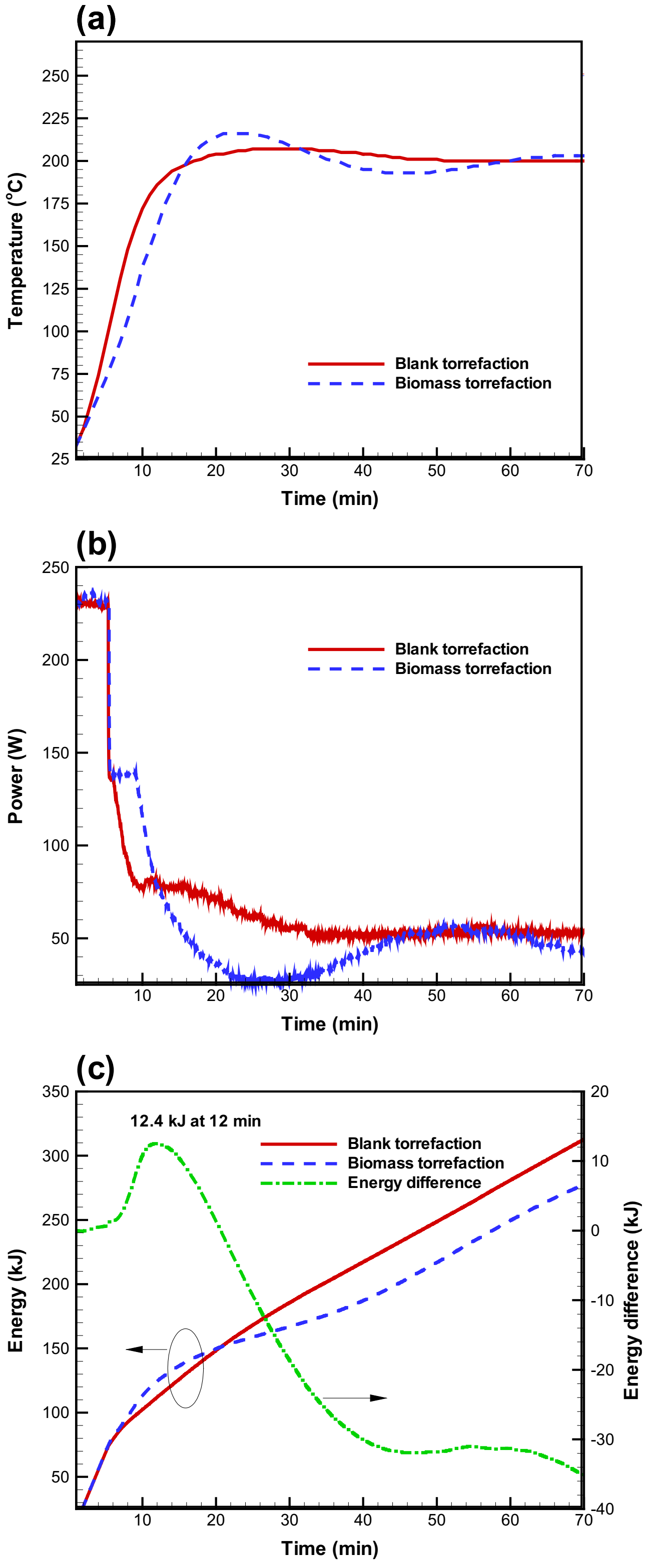


Fig. 5. Temporal distributions of (a) temperature, (b) supplied power, and (c) supplied energy for oil palm fiber torrefied at 200 °C.

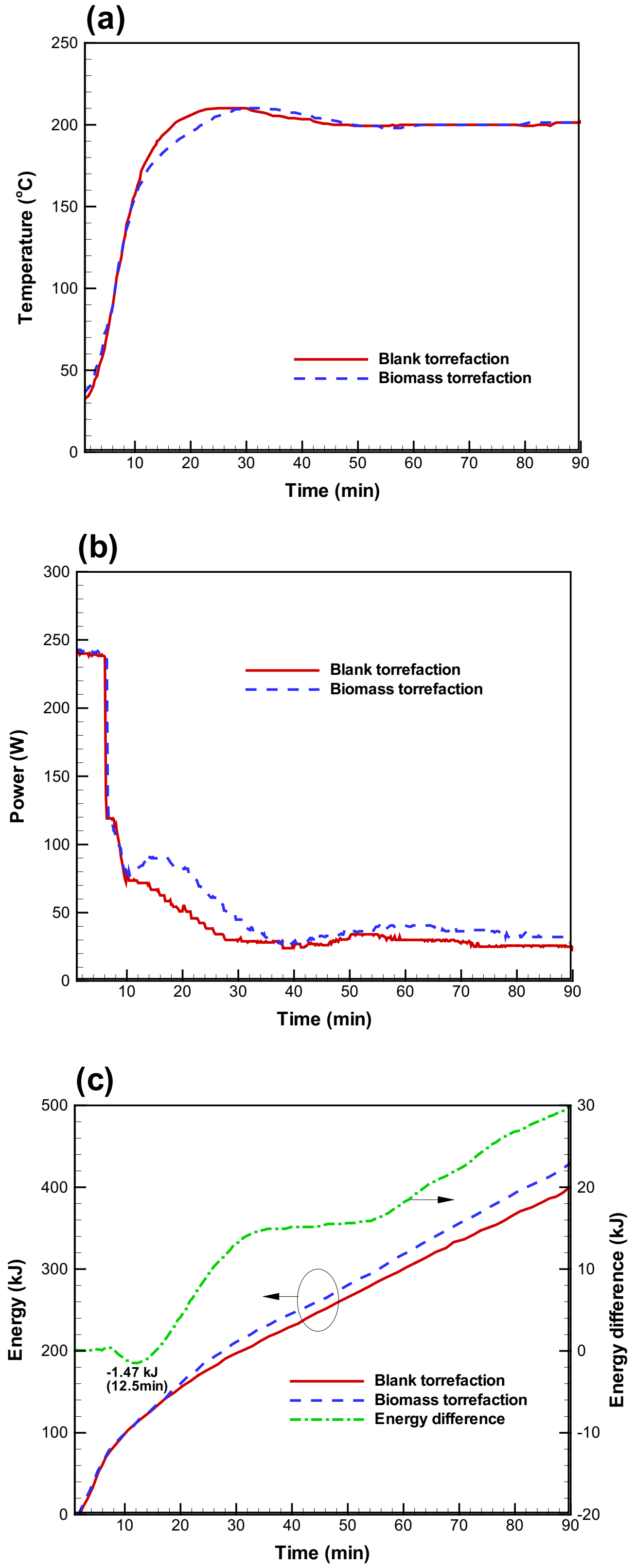
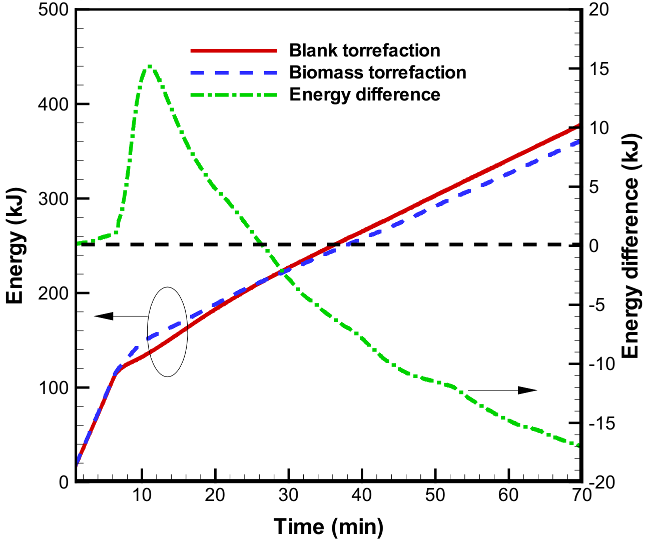


Fig. 6. Temporal distributions of (a) temperature, (b) supplied power, and (c) supplied energy for eucalyptus torrefied at 200 °C.

consumed energy decreases with time marching when the time is longer than 14 min. This may be due to the lignin decomposition in the torrefaction. The thermal decomposition of cellulose is endothermic in nature. However, the studies of Mok and Antal Jr. [33] and Milosavljevic et al. [34] mentioned that cellulose thermal degradation might become exothermic when the char formation process was significant. Cho et al. [35] also pointed out that the cellulose pyrolysis might be exothermic at low temperatures. Consequently, the decreased energy consumption may also be attributed to the charring process from cellulose pyrolysis.

3.5. Net reaction heat for torrefaction

The values of net energy for the torrefaction of the two biomass materials at 200, 250, and 300 °C are shown in Fig. 9. It is apparent that an exothermic reaction is exhibited when oil palm fiber is torrefied at 200 or 250 °C in that the heat of reaction is negative. This is mainly attributed to hemicellulose reaction in the light and mild torrefaction where the hemicellulose content in the oil palm fiber is high. When oil palm fiber is torrefied at 300 °C, the consumption of cellulose is an important factor in determining the thermal behavior. Therefore, the severe torrefaction of the biomass becomes endothermic. When eucalyptus undergoes light, mild, or


(a) Oil palm fiber

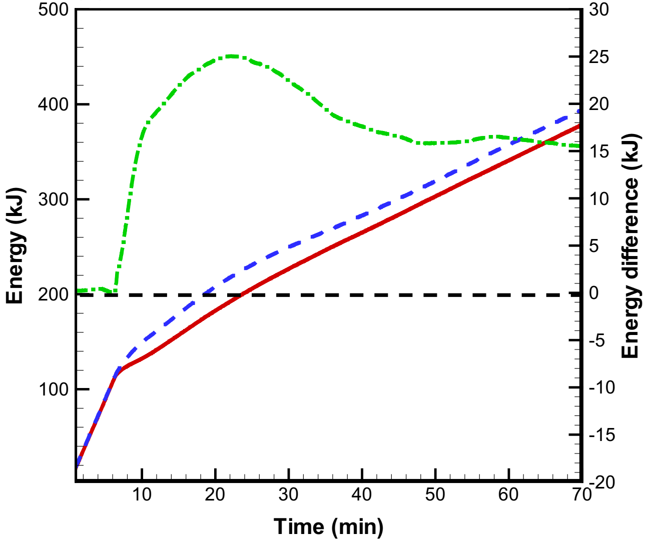
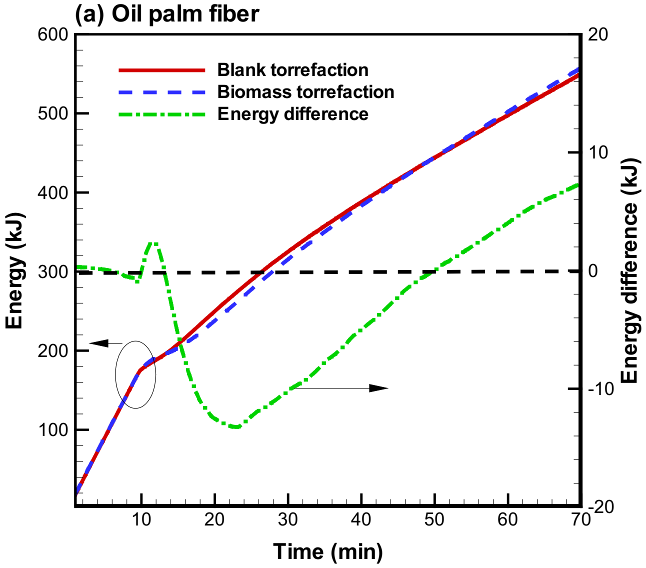

(b) Eucalyptus

Fig. 7. Temporal distributions of supplied energy and energy difference for (a) oil palm fiber and (b) eucalyptus torrefied at 250 °C.


(a) Oil palm fiber

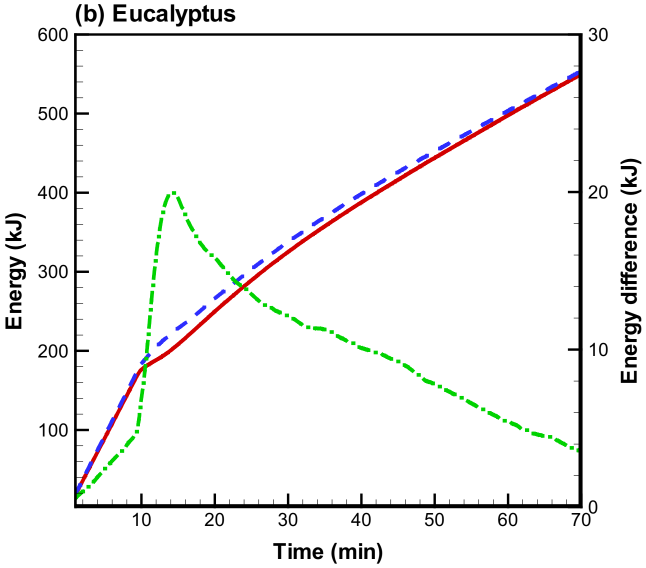

(b) Eucalyptus

Fig. 8. Temporal distributions of supplied energy and energy difference for (a) oil palm fiber and (b) eucalyptus torrefied at 300 °C.

severe torrefaction, the reaction is always endothermic. This can be explained by relatively low hemicellulose content and high cellulose content in eucalyptus. The study of van der Stelt [27] revealed that the thermal behavior of beechwood during torrefaction became less endothermic or more exothermic with increasing torrefaction temperature. In the present study, similar phenomenon is observed in eucalyptus torrefaction. Both beechwood and eucalyptus belong to ligneous biomass. Therefore, the obtained results are qualitative agreement with the measurements of van der Stelt [27]. For eucalyptus torrefied at 300 °C, it can be thought of as thermal neutral at the end of the torrefaction because the net reaction heat is close to zero. This thermal characteristic at the severe torrefaction is likely due to the exothermic reaction of lignin. Because the operation of biomass torrefaction is subject to heat supply in the reactor, the above observations of thermal behavior have provided a useful insight into the design of torrefaction reactors.

In the study of Chen and Kuo [1], the co-torrefaction characteristics of hemicellulose, cellulose, and lignin at three temperatures of 230, 260, and 290 °C were studied, and the thermogravimetric analyses suggested that no synergistic effect from the co-torrefaction was exhibited. On the other hand, the study of Wang et al. [41] indicated that the interaction of cellulose and hemicellulose strongly promoted the formation of 2, 5-diethoxytetrahydrofuran and inhibited the formation of altrose and levoglucosan, while the presence of cellulose enhanced the formation of hemicellulose-derived acetic acid and 2-furfural in the temperature range 350–500 °C. These results reveal that the interaction of hemicellulose, cellulose, and lignin may depend on the reaction temperature, and the thermal behavior from the interaction deserves investigation in the future.

4. Conclusions

An experimental system has been conducted to explore the thermal characteristics of oil palm fiber and eucalyptus in the course of torrefaction. From the thermogravimetric analysis, the thermal behavior of biomass can be described in terms of the consumptions of hemicellulose, cellulose, and lignin. Seeing that the contents of the three constituents depend on biomass species, the net reaction heat for the torrefaction of oil palm fiber is different from that of eucalyptus. The thermal decomposition of hemicellulose in oil palm fiber at 200 or 250 °C is important, so the torrefaction is characterized by an exothermic reaction. The hemicellulose in eucalyptus is not as rich as in oil palm fiber; therefore, the thermal degradation of cellulose is important and the torrefaction of eucalyptus at 200 or 250 °C is endothermic. With the torrefaction temperature of 300 °C, the role played by cellulose on the thermal behavior is important. Consequently, the severe torrefaction reactions of oil palm fiber and eucalyptus are endothermic. Char formation from the thermal degradation of cellulose and lignin decomposition may become crucial in contributing heat at the torrefaction temperature of 300 °C. Consequently, the severe torrefaction of eucalyptus is almost characterized by thermal neutral. As a whole, the thermal behavior of oil palm fiber from torrefaction is less exothermic or more endothermic with increasing torrefaction temperature, whereas an opposite tend in eucalyptus torrefaction is observed. The thermal behavior of

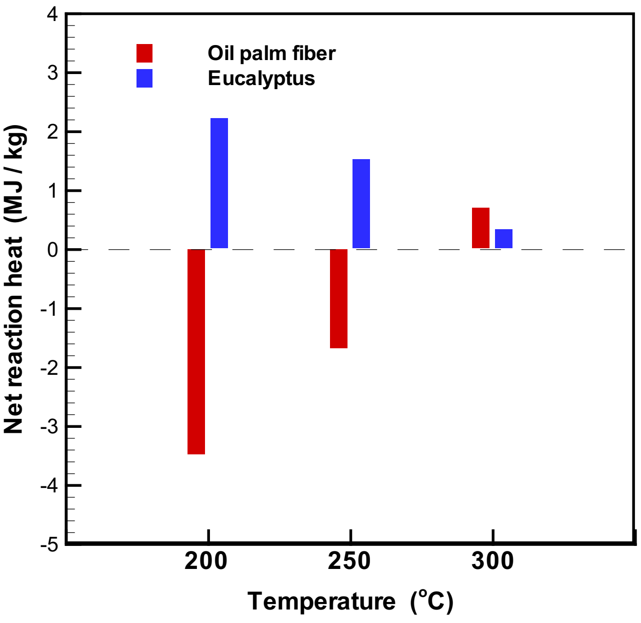


Fig. 9. The net reaction heat for biomass in torrefaction.

biomass torrefaction is of the utmost importance for the operation of biomass upgrade and pretreatment. Accordingly, the obtained results have provided useful information for the design of reactors for fulfilling biomass torrefaction.

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